

## Eco-wall modular solutions for buildings

AMADO, M.<sup>1</sup>; PINHO, F.<sup>2</sup>; FARIA, P.<sup>3</sup>; RAMALHETE, I.<sup>4</sup>

**ABSTRACT:** This paper discusses the development of modular solutions for eco low-cost houses based on a pre-fabricated modular wall system environmentally sustainable, socioeconomically competitive and geared towards developing African nations with a housing deficit. The key point to the research of a modular wall solution is a structural layer complemented with local and materials made by non-specialized workforce. This wall also meets also hydrothermal acoustic and mechanical properties. Thus, the solution also offers good safety and interior comfort conditions to its users while maintaining the flexibility to expand the size of the house. Parameters as dimensions, materials and constructive processes of the existing housing stock were studied. Features such as the family size, typology, different uses, common materials, existing regulations, minimal living conditions, safety and comfort have also been considered to achieve the most efficient solution.

*Keywords: Sustainable Construction; Pre-fabricated Wall; Ecological Materials*

### 1 INTRODUCTION

In the next four decades, it is expected that the populations from African countries will have a rapid growth due its fast economic development [1]. This situation is leading to rural exodus i.e. internal migrations from the rural areas to urban centres where there is an economical cycle that provides employment. These rural populations are mostly from the poorest countryside areas and start to occupy cities outskirts, giving rise to slums deprived of infrastructural conditions. The slums are formed by precarious housing, namely shack, made with inadequate materials in terms of structural and safety stability as well as hydrothermal comfort for occupants.

According to article 25 from Human Rights, “(...) *everyone has the right to a standard of living adequate for the health and well-being of himself and his family (...)*” [2, 3]. However, in developing countries this situation is problematic with 62% of Sub-Saharan Africa population living in slums in 2012 . In most cases, the access to a house does not provide minimum level of services i.e. does not have an efficient urban structure nor utilities to solve this situation. As a consequence, these populations are socially excluded from the rest of the city; worsen their social and economical conditions. Faced with this situation, the developing countries governments and other entities are trying to create housing models that consider the population social and economical conditions and its rapid growth. However, these housing programmes are difficult to apply due to insufficient funding associated with a weak industrial sector and unskilled labour. This context brought out the necessity

---

<sup>1</sup>) Assistant Professor, Faculty of Sciences and Technologies of NOVA University of Lisbon, Civil Engineering, ma@fct.unl.pt

<sup>2</sup>) Assistant Professor, Faculty of Sciences and Technologies of NOVA University of Lisbon, Civil Engineering, ffp@fct.unl.pt

<sup>3</sup>) Associate Professor, Faculty of Sciences and Technologies of NOVA University of Lisbon, Civil Engineering, paulina.faria@fct.unl.pt

<sup>4</sup>) PhD Architect student, Faculty of Sciences and Technologies of NOVA University of Lisbon, Civil Engineering, i.ramalhete@fct.unl.pt

to develop a faster and low-cost construction model that fosters a self-building process using local materials. This model is able to lead to environmental improvement, to a fair resource management and also to a better quality of life.

This is a situation that is able to change with the implementation of new ideas and new ways in order to achieve sustainable solutions for people and for environment. It is crucial that society should focus the investment in infrastructure and housing in order to assist the communities to build their own affordable houses according to their income through an incremental process. This process will allow the society to contribute for the solution to housing problem, through different times and scales, in a city that has already an infrastructure system that supports development. In this new approach there is a potential to the application of prefabricated materials to build houses in order to provide an instant solution and contribute for a sustainable development.

The presented research refers to the development of a thin modular prefabricated panel made with reinforced concrete that is complemented with local materials, namely external and internal complementary elements. Eventually, local materials with insulation characteristics can be added between the interior face of the panel and the masonry wall. This prefabricated module meets hydrothermal, acoustic and mechanical requirements which are important for building quality and internal comfort. This modular panel will develop a flexible house based on household familiar and economical dynamic supported by an incremental process, which allow the user to expand or retract the house according to his needs. The application of a modular structure complemented with local materials shows a feasible solution for housing deficit in developing countries. It can improve quality of live through the following actions: a prefabricated standard solution is cheaper and easier to assemble; the use of local materials creates local employment and thus local economy; the application of materials more adapted to local climate are more efficient in terms of hydrothermal comfort.

The Eco-Wall project has two main approach strategies: the first the idea is to produce the modular panel in Portugal and then complemented in situ with local materials; the second approach depends on the target-territory development, the wall is produced locally as well as the complemented materials. This last will reduce transportation costs and promote a contribution for the local economy strategy.

The research stills under development and the present results refer to Eco-Wall composition in terms of optimised layout and materials. Further research intends the hydrothermal and acoustic tests and the flexible layouts for housing models.

## **2 RESEARCH OBJECTIVS**

The Eco-Wall modular solution is a project that aims to contribute to solve house deficit in developing countries namely Angola, Mozambique, Cape Verde and Guinea-Bissau. The solution considers socioeconomically and environmental values in order to provide a cheaper, safety, fast to assemble and environmentally adapted solution.

In terms of economic issues, this prefabricated modular solution becomes viable for these countries because its production is cheaper and, due to its standard model, becomes easy to assemble in a context of self-construction. Thus, the application of this solution is more affordable for the user showing a cost reduction of 30% [4], [5]. The presented prefabricated modular solution supports the flexible house concept that has also economic advantages for the user i.e. the house is expandable according to household income and needs. The manufacturer has also economic advantages by using a prefabricated module namely in terms of waste reduction and energy consumption. According to Stallen et al. the usage of prefabrication results in 52% less construction waste [6] and the water and energy consumption is reduce in 50% [7] because all the process is rationalised in terms of costs

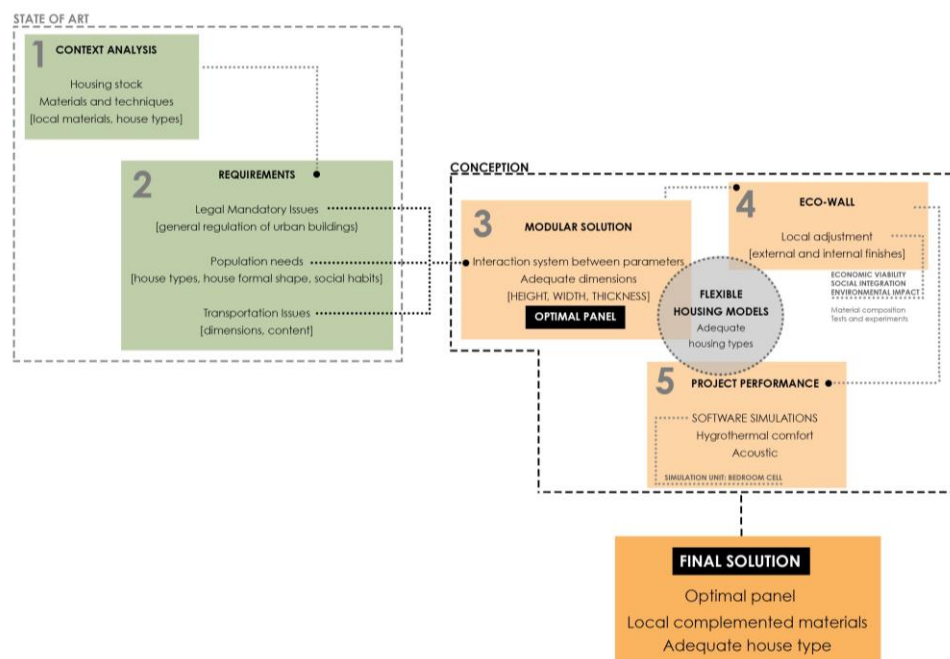
and resources which is also environmentally viable. Another objective related to this prefabricated modular solution is the capacity of being easily handled by the user, under a self-building process. Thus, the modular panel conception is a crucial part to ensure the solution efficiency because in this step the optimal dimensions are defined (namely height, width and thickness) which are important requirements for the user.

The presented modular solution is complemented with local materials, which has economical and environmental advantages can be resume: Application of local materials contributes for local economy because products are made locally by the community, providing employment. Local production reduces transportation costs and thus the products become more affordable for the community; Social and cultural terms, local materials have a connection with the site and its cultural identity i.e. the application of local materials allied to a self-building process allow community participation, making their acceptance easier; Environmentally, the use of local and natural materials long-distance transportation, which means less energy consumption and thus less harmful emissions [4].

The present research aims to contribute for the solution of housing deficit through the implementation of a flexible house built with a prefabricated modular panel that ensures structural stability, which is complemented with local materials that develop local economy and promotes social participation.

### 3 METHODOLOGY

The applied methodology, structured by five steps, supports the research process to the creation of an adequate modular solution that is adaptable to different socioeconomically, cultural and environmental contexts (Figure1). Steps 1 and 2 correspond to the context data for the formulation of modular solution, providing the theoretical body of the research. Steps 3 and 4 focus on Eco-Wall conception composed by an optimal panel complemented with local materials. The fifth and sixth steps are the validation and consolidation of the previous phases. In these steps are made the internal comfort simulations and the definition of the adequate housing types for the target-countries. Findings of the solution are formed by three parameters: an optimal panel, local complemented materials and an adequate house type.



**Figure 1.** Research Methodology.

Step 1 refers to a territorial analysis in terms of housing stock characteristics namely local building techniques, used materials and prevailing house types. This analysis identifies and defines the problematic, the current housing deficit and also provides an overview of the available resources and commonly used building techniques.

Step 2 step defines the requirements related to legal issues (General Regulation for Buildings) and socioeconomically criteria. Legal mandatory issues provide the definition of required minimum standards for living, as the room areas and the floor height, in order to ensure minimum quality parameters. The social and cultural characteristics contribute for the definition of the housing functional schema and its dimensions, based on social habits and needs. In the second step it is also considered the transportation logistic, namely in terms of dimensions in order to transport the maximum amount of panels in the available space of a High Cuba 40' sea container.

Thereby, step 2 results in a set of parameters that are the main basis for the modular panel conception in step 3. In this following step, the parameters are interacted with each other in order to achieve an optimised modular panel in terms of adequate dimensions for transportation and population needs as well as ensuring minimum standards based on legal regulation. In this step, the panel height and width results directly from the identified requirements in step 2 (legal requirements, population needs and transportation issues); however, the panel thickness is obtained by mechanical resistance tests. In order to accurate these dimensions, a specific test system for compression and traction testes were developed.

Thus, step 3 establishes the modular panel that will be implemented on a flexible housing model. This panel is able to be applied as a universal solution for low-cost housing in any context i.e. the panel is the main structural basis for the house and its adaptation to socioeconomically and territorial context is assign by step 4 of local adjustment.

Step 4 refers to the study, test and experimentations of complemented materials, namely the external and internal complementary elements, that will ensure the adequacy to territory i.e. the adaptation of the building system and materials to socioeconomically and environmental context. The selected materials are analysed in terms of composition in order to find an economically viable solution, with low environmental impact and socially well integrated. This step results in the Eco-Wall (Ecoefficient Wall) solution composed by a *structural sheet* (the panel) covered with local and eco-efficient materials.

The final step (step 5) is the project performance entrenchment i.e. the consolidation of the solution through hydrothermal and acoustic software simulations in order to achieve an adequate comfort level in the target-countries context. These simulations are made in the flexible room-unit, the bedroom, defined in step 3, that provides the base values.

Steps 3, 4 and 5, which form the conception part of the process, result in flexible housing models formed by the Eco-Wall already optimised and simulated for the selected target-countries. The flexible housing models considers all the parameters previously identified, namely the prevailing house layout, social habits and household dynamics expressed in step 3 combined with the Eco-Wall characteristics. This will allow an adequate incremental application of the Eco-Wall modular housing model.

The final solution corresponds to the combination between an optimal structural panel complemented with local materials that form a flexible house whose incremental process is applied according to household needs and income.

The present research stills under development in step 4 i.e. the current paper corresponds to the results appointed to Eco-Wall formulation.

## 4 DEVELOPMENT PROCESS

The presented project shows how can modular housing solutions emerge as a new answer for housing deficit in developing countries and also contribute for a sustainable development. The implementation of flexible housing models requires an incremental strategy of expansion or contraction according to household characteristics, namely its dynamic and income that compromise the housing model adequacy. These two conditions are crucial for incremental housing efficiency because, in most cases, people cannot afford a house for a long-term period and they end up living in informal settlements where they build according to their economic conditions. However, an evolutive process that allows the house expansion according to people economic capacity enables them to acquire a house with the minimum requirements (infrastructures and shelter) and improve it later.

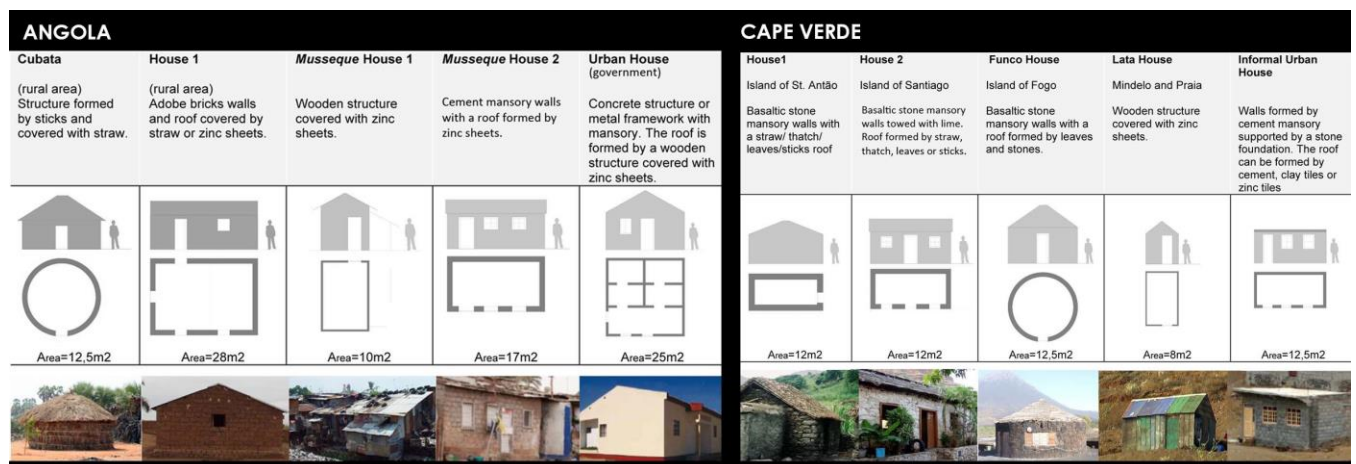
The adaptation to household dynamics of each market-country is one of the main premises in conception process in order to ensure a functional high standard. Thus, the objective is that the house should be an integral part of a continuous process where the transformations may occur whenever necessary. The house layout should consider the functional requirements of the household, namely its relation with outdoor areas or economic activities related to it. The modular housing model should also provide different schemas and layouts in order to provide variety to the housing programmes. These different flexible models can be manipulated through the following operations that set the housing grammar: aggregation; subtraction; division; extension to vertical and/or horizontal direction.

### 4.1. Step 1: Context Analysis

The first step is the housing context analysis in the target-countries – Angola, Cape Verde, Guinea-Bissau and Mozambique – that enables the creation of a diagnosis about housing conditions as well as the commonly used materials and building techniques. This analysis is important because will focus the solution in the identified problems and will inform the available materials and building techniques dominated by local people, under a perspective of self-building.

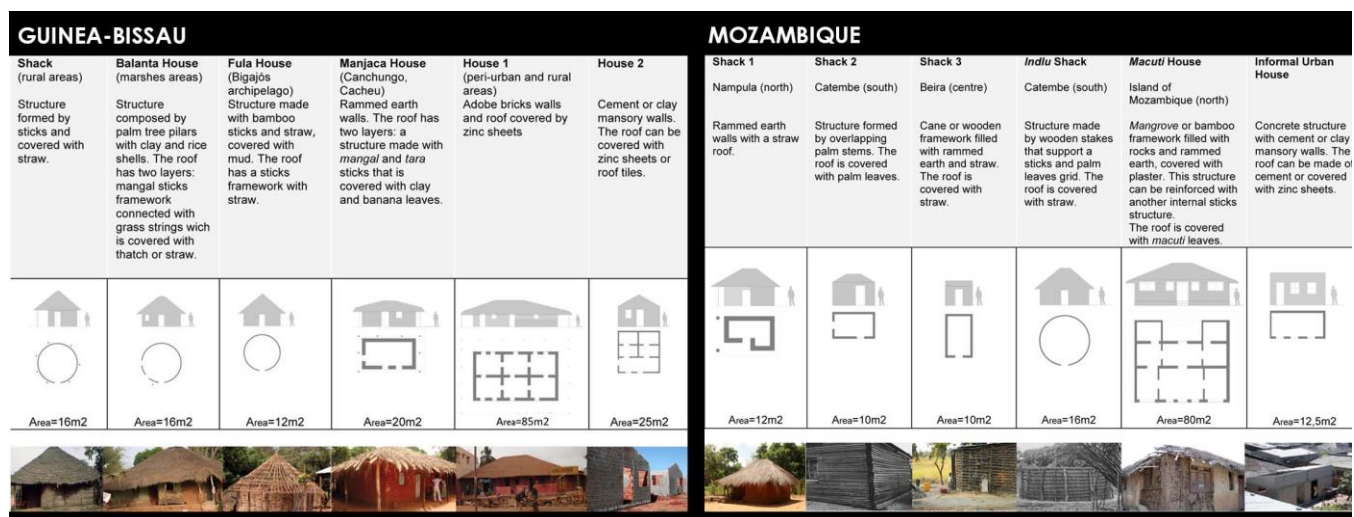
Figure 2 and Figure 3 show two types of prevailing layout grammars: rectangular and circular layout mostly with only one room. While the rectangular form is dominant in Angola, Cape Verde and Mozambique, the circular form is prevailing in Guinea-Bissau.

In most cases, the functional rooms (cooking area and water closet) are outside for two main reasons: due to health concerns and the absence of a sewer infrastructure, the water closet is attached to a septic tank outside; the cooking area is located outside due the fire risk and heat production from the cooker or fire place. In informal settlements housing, the front of the house is an important space for social interaction between neighbours, which simultaneously works as trade area



**Figure 2.** Housing stock analysis of Angola and Cape Verde.





**Figure 3.** Housing stock analysis of Guinea-Bissau and Mozambique.

The analysis shows also that the commonly used materials are rammed-earth, adobe bricks, wood and straw although there is a strong presence of basaltic stone in Cape Verde architecture. It is important to refer the differences between the materials used in urban and rural settlements because reflects the available materials in each area: composite materials, link zinc sheets and cement bricks, are dominant in urban areas due the lack of natural resources and the proximity with industrial poles; organic or natural materials, like adobe or wood, are prevailing in rural areas because they are the only available materials nearby.

The analysis of local materials is important to modular low-cost houses conception because this kind of materials offers economic advantages compared with imported materials, a fact to be taken into account during the research.

## 4.2. Step 2: Requirements

In this step are defined the general requirements of each target-country related with legal premises, social and cultural criteria and transportation conditions.

### Legal mandatory issues

The legislation and the regulations about the housing programs are an important database support for the identification of required minimum standards. Principles ensure that all citizens shall have a suitable home. In this context, a house should guarantee the following functional requirements: safety; hygiene, health and hydrothermal comfort; fitness-for-use criteria. Table 1 shows an example of a two-bed house, which established the minimum house area for a family with a child.

**Table 1.** Required minimum standard for a two-bed house.

Country	Typical floor height	Bedroom area	Living room area	Kitchen area	WC area	Fenestration area	Total area (social housing)
Cape-Verde	2.6m	10,50m <sup>2</sup>	14m <sup>2</sup>	6,50m <sup>2</sup>	4,50m <sup>2</sup>	1,00m <sup>2</sup>	52m <sup>2</sup>
Angola	2.8m	10,50m <sup>2</sup>	10m <sup>2</sup>	6,00m <sup>2</sup>	-	1,08m <sup>2</sup>	52m <sup>2</sup>
Mozambique							
Guinea-Bissau	2.8m	9,00m <sup>2</sup>	12m <sup>2</sup>	-	-	1,00m <sup>2</sup>	-

## Population needs

The population needs parameters focus in living and familiar characteristics of the household, which are important for the conception phase, namely the house layout. Through the housing stock analysis it is possible to identify common features among the four countries involved: the housing stock is mainly formed by single-family residences with one or two rooms; outdoors are simultaneously social and dining areas, including cooking and meals preparation; the front door perimeter is a social and commercial area.

The housing stock and socioeconomically analysis of the referred countries show a predominantly rural society in general whose main economical activities are focus in fishery and agriculture, depending on the geographic context, or in local trade and crafts. These characteristics are crucial for the house functional layout in order to generate a multifunctional house to live, to produce and to profit.

## Transportation

The Eco-Wall project, as already mentioned, has two operative stages: in the first stage, the modular panel is produced in Portugal and exported to target-countries. There, the panel is complemented with local materials and mounted by the community. The second stage depends on the target-country development i.e. it is expected that the panel will be produced locally as well as the complemented materials.

However, taking into account the first scenario, the research considered the panel transportation through sea containers. In order to reduce the transportation cost share and facilitate the logistic process, the research considered the dimensions of a High Cuba 40' model sea container i.e. the panel optimization in step 3 will take into account the suitable dimension for its transportation. The High Cuba 40' sea container has 12,36m in length, 2,34m in width and 2,68m in height.

### 4.3. Step 3: Modular solution

The parameters identified in previous steps are interacted in the third step in order to achieve the optimal panel dimensions. The first consideration, as already mentioned, is that the panel is made with reinforced concrete. This choice lies on structural resistance of reinforced concrete that ensures structural quality to the house. The selected components materials for the panel are currently used in civil engineering and architecture and as such are readily available and thus cheaper: concrete C25/30 or C30/37; Structure class A500, type NQ50; Steel profiles class S280GD+Z, U shape [8].

However, the use of concrete has environmental impacts namely due the production of cement. In order to soften these impacts, several tests were developed, which experimented the addition of earth (soil) to concrete mixture, partially reducing the content of cement. These tests showed the physical and mechanical behaviour of concretes with different percentage of earth in the cement, namely to verify its durability, comparing with current cement aggregates [9]. During these tests, it was observed that homogenisation of the mixture, and namely of the soil, is one of the most important steps because if the blending is not mixed well it can compromise the concrete quality [10]. More can be develop, namely to assess concrete behaviour with cork waste, ceramic wastes and textile fibers, based on previous research on mortars in order to achieve different and efficient solutions [11]–[14].

The conception process started by the definition of required minimum standards for room areas, according to General Regulation for Buildings of each country and considering the most stringent values. Table 2 shows a summary of the average values from each studied country.

**Table 2.** Summary table of required minimum standard of each country.

Typical floor height	Window width	Areamin Bedroom	Areamin Living room	Areamin Kitchen	Areamin Water Closet	Areamin Frenestration	Areamin T2
2,8m	0,90m	10,50m <sup>2</sup>	14m <sup>2</sup>	6,50m <sup>2</sup>	4,50m <sup>2</sup>	1,08m <sup>2</sup>	52m <sup>2</sup>

The panel height was directly obtained from the minimum standards required with 2,8m. The width calculation considered the panel weight and dimension for its transportation and handling by the user, resulting in 11 types of width between 0,5m and 1,5m. Subsequently, the number of needed panels to form a room was quantified, according to the minimum area standards. After defining the optimal area calculation for each room a score table between 1 and 11 points was considered to evaluate each panel was considered. The best score was the result between the minimum standards for room area and an optimal width. If the resulting areas are the same but made with different panel widths, the panel that needs fewer modules to make the area prevails.

The final typologies score was the result of a total sum between all the possible panel widths for all types of room as shown in Table 3.

**Table 3.** Final score of each panel widths and each room type.

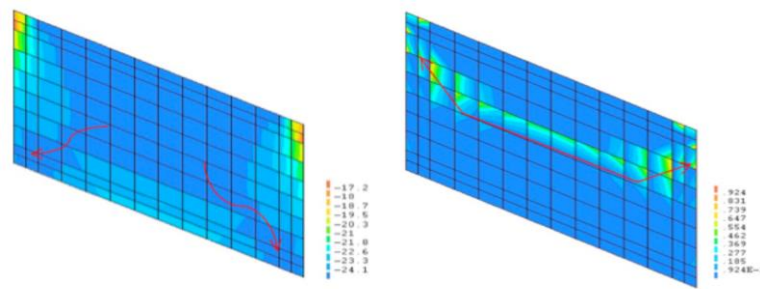
Panel Width	Score for each panel width according to room				Σ Score	Rank
	Bedroom	Living room	Kitchen	WC		
0,5	11	11	8	9	39	2 <sup>o</sup>
0,6	10	8	10	6	34	3 <sup>o</sup>
0,7	7	9	4	5	25	5 <sup>o</sup>
0,8	6	5	6	7	24	6 <sup>o</sup>
0,9	4	4	7	10	25	4 <sup>o</sup>
1	8	6	2	4	20	8 <sup>o</sup>
1,1	9	10	9	11	39	1 <sup>o</sup>
1,2	5	3	3	8	19	9 <sup>o</sup>
1,3	1	7	11	3	22	7 <sup>o</sup>
1,4	3	2	5	2	12	10 <sup>o</sup>
1,5	2	1	1	1	5	11 <sup>o</sup>

The most efficient panel has a width of 1,10m, followed by panels with a width of 0,5m and 0,6m. As Table 3 shows, the panels with a width of 1,1m and 0,5m have the same score but the one with a width of 1,1m has less accessories and connectors, which means that it has less production and assembly costs and is built faster. Furthermore, this dimension will allow the integration of windows only with the production of two more panels with the following dimensions: 1,10x1m and 1,10 x 0,8m.

The optimal panel reveals concerns about the transportation; once that the sea containers selected have 12,36m in length, 2,34m in width and 2,68m in height, it is possible to export 4 rows of panels in length (12,06m/2,80m), multiplied by 2 (2,68m/1,1m).

The main objective was to achieve the minimum thickness possible with mechanical resistance. The panel thickness calculation was constrained by covering the internal structure (*Malhasol*). Knowing that the distance between the internal structure and the covering should not be inferior to 3cm, the required minimum panel thickness is 7cm. The behaviour of the panels have then been study by simulation (Figure 4).





**Figure 4.** Panel compression and flexural behaviour.

Another issue of this panel is the section asymmetry: the panel thickness is displacing from its centre in order to allow the application of a complemented material (which means the panel is strictly structural) in step 4. The structural metallic profiles, apart from working as connectors between panels, also ensure the connection between all the construction components (panel and complementary layers).



**Figure 5.** Modular panel section.

The structural metallic profiles have U shape with the following dimensions: 100mm x 50mm x 3mm. The concrete is attached by a half of its thickness, remaining 65mm for the complemented material application (Figure 5).

The flexible housing model made with these panels can be easily transformed and expanded because all the connectors and joints work mechanically which also is an advantage in a self-building strategy. With this solution, and based on the African low-income households dynamics, the family has a small house, that provides shelter and infrastructures, and over the years it will evolve according to the family members and its financial situation.

#### 4.4. Step 4: Eco-Wall

The fourth step refers to Eco-Wall composed by the optimal structural panel with the local complementary materials that form the wall envelope. The selection of materials for internal and external finishes was based on climatic and territorial context of each country studied in state of arte (steps 1 and 2).

The three main premises of Eco-Wall are its economical viability, social contribution and low environmental impact. In this context, the optimal panel is complemented with local and durable materials that contribute for local economy, reduce transportation costs and also ensure quality, which reduces maintenance costs. The materials selection involves also cultural and social criteria, namely the settlement identity in order to create an inclusive process between community, territory and settlement.

The present research considers the application of an earthen-based blocks masonry interior wall – made with compressed earth blocks (CEB) or adobe. According to housing stock analysis in step 1, these blocks and type of masonry are commonly used in the four target countries and meet economical principles and cultural expression. They can be seen in traditional architecture, and environmental concerns due to the abundance of raw material and efficiency when efficiently applied are very positive. Furthermore, the application of an earthen block masonry wall as a complementary

element can improve the wall's technical performance and ecological efficiency. In fact, due to its natural and ecological proprieties and processes, they represent low energy consumption during the production and transport process, together with an important contribution for comfort. Therefore the earthen blocks can easily be produced by the communities, implementing socio-economical advantages.

In this context, the production of several common and easily produced earthen blocks was observed and samples are being tested. The aim is to define the minimal characteristics that the earthen masonry blocks must present, in order to offer eco-efficiency. The blocks were produced with different types of soils and additions, namely low percentages of mineral binders as cement or hydraulic lime, construction and demolition wastes (CDW) and other types of non-dangerous wastes. They were also cured in different ways, what may be particularly important when they are stabilised. Samples from different geographical areas were used: CEB with CDW, stabilised with hydraulic lime from Montemor, Portugal; CEB stabilised with air lime and cement provided by Soilbloc, Spain; non-stabilised adobe from Évora, Portugal; non-stabilised adobe from Montemor; the same previous block but after low firing treatment, also from Montemor. Through these samples it is possible to compare different proprieties related to geographical area – although not yet with earth from the target countries; soil, binders or industrial waste used; if they are handmade or industrially produced (moulding, compression, firing or non-firing, etc... [10] The tests that are being developed in the mentioned samples are: tensile strength; compressive strength; resistance to wear by dry abrasion; water abrasion resistance; dimensional stability to temperature variations and relative humidity; water absorption by low pressure; water absorption by capillarity; drying capacity. These tests are based on current standards and procedures. Some of the durability aspects that are tested will not be needed if the masonry wall is applied by the interior of the modular panels, situation that appears to be preferred in the target-countries, where earth masonries are still associated with low durability and low-income housing – a situation that is totally inverse to the one experienced in the most developed countries of the world, where earth as a building material is nowadays seen as a high standard eco-efficient material. In order to make the masonry, the blocks should be applied with mortars that are compatible with the blocks' characteristics, and that are also being tested.

In order to improve the thermal performance of the Eco-Wall, it is considered the application on an extra layer between the masonry wall and the structural panel. Based on context analysis made to target-countries, the application of a straw or canes *sheet* is able to improve the thermal behaviour of the Eco-Wall, which in sub-Saharan African countries focus in cooling and ventilation. As the earthen blocks production, the application of this kind of material provides a new source of income to local communities, improving local economy [10].

For external finishes a painting system can be easily applied over the modular concrete panels. For internal finishes the research considered two possibilities that are focus in the quality and healthiness of indoors areas: applications of ecological plasters and wallpaper.

A workshop was made on ecological mortars and plasters based on earth and that incorporate natural fibbers and, eventually, low portions of lime, and test have been made for half a year. Concerning the natural fibbers, the tests already made show that the fibbers percentage should not be very high because the plaster becomes vulnerable to crash [10]. However the earthen-based mortars made during the workshop, which were applied in different types of walls (concrete, stone, adobe, brick and straw bale masonry, for example), show several advantages, namely: diversity in terms of colour shades according to the used soil; when there is no addition of lime it is easy to repair through water application; the capacity to absorb and release internal humidity allowing the natural hydrothermal adjustment; the good workability and easiness of application [15].

The research also considered the application of recycled wallpaper composed by agricultural wastes in internal walls that can be produced in target-countries and also improve the wallpaper blending aggregation and mechanical performance [16]. A resource management based on production forests

should support the use of wood-base products, like wallpaper. Thus, materials derived from wood become environmentally sustainable due its inexhaustible raw material. The application of agricultural wastes is also an advantage in the target-countries context, i.e. Cape Verde, for example, produces agricultural waste like corn stalk and banana stems that have low or non-commercial value. The use of these residues creates another source of income for local people, namely in rural areas.

Nevertheless, the sustainability of wallpaper needs to consider not only the blending but also its application to inner walls, namely in which refers to glues, paste or another kind of chemicals i.e. the use of harmful chemicals or synthetic materials that can compromise the environmental efficiency of the solution. The chemicals might be present in binders, glues and pigments, invalidating the full recycling process and generating harmful gases to ecosystem with long-term damaging consequences for environment and people.

In order to provide a full recycling process, the proposed wallpaper is glued with a natural adhesive composed by wood pulp and water named *Methyl Cellulose*. Besides being an organic compost, this material does not present health risks or environmental threats, is non-toxic and non-allergic, contributing for the efficiency and adequacy of the solution [16] [17] [18].

*Methyl Cellulose* is a natural chemical powder derived from cellulose that is dissolved in cold water (between 40°C and 50°C) and becomes a viscous gel with adhesive proprieties. The firing process requires low temperatures and therefore low energy consumption [17]. Beside its adhesive proprieties, this chemical compound is a natural emulsifier that can be added to the paper blending, improving its water absorption resistance, which is an advantage for inner walls performance [16].

The application of organic materials made locally show economical and environmental advantages. In terms of environmental benefits, these types of materials integrate natural wastes with low or non-commercial value and also avoid exploitation of natural resources strictly for construction materials production. In economic terms, the use of wastes in order to improve materials presents advantages due its commercialization that creates a new source of income for the communities and stimulates local economic cycle.

## 5 CONCLUSIONS

The population growth in developing countries calls for an urgent housing solution with economically viability in an environmental long-term strategy that ensures a sustainable development for these populations. Prefabricated solutions have the potential to provide a faster solution with contributions to a long-term solution in terms of social, economical and environmental.

The research methodology leads to the conception of a sustainable building solution for flexible houses with a capacity to be applying in developing countries. This Eco-Wall solution is based on a structural module complemented with local materials. The combination of socioeconomically, environmental and territorial parameters has been considered in order to adequate the final solution to Sub-Saharan African countries like Angola, Cape Verde, Guinea-Bissau and Mozambique. Nevertheless, this research methodology can be implemented to different territorial context thought the adaption of context requirements and its application to steps 4 and 5 (local materials selection and project performance).

The solution resulted in a thin optimal panel made with reinforced concrete, which ensures structural stability, whose the dimensions resulted from target-countries requirements and also compression and flexural simulation and tests.

The panels and complemented materials build the Eco-Wall fulfilling aesthetical, hydrothermal, acoustic and mechanical requirements, which are important for building quality with internal comfort.

All the mentioned parameters consider a construction process made by non-specialized workforce in order to reduce building costs.

Further research will complement the experimental campaign by panel prototype tests and focus step 5 (project performance) in order to validate and consolidate the solution in terms of internal comfort through software simulations.

## REFERENCES

- [1] UN-HABITAT, "The State of African Cities 2010: Governance, Inequality and Urban Land Markets," UN-HABITAT, Nairobi, 2010.
- [2] UN-HABITAT, "The Right to Adequate Housing," Office of The United Nations High Commissioner for Human Rights, Geneva, 2009.
- [3] United Nations, "The Millenium Development Goals," United Nations, Nova Iorque, 2013.
- [4] T. Lopes, M. Amado, and F. Poggi, "Construção Sustentável - Fase de Pré-Concepção," presented at the 4º Congresso Nacional da Construção, Coimbra, 2012.
- [5] P. Waskett, "Current Practice and Potential Uses of Prefabrication," Building Research Establishment Ltd, Watford, Project Report, 2003.
- [6] M. Stallen, Y. Chabannes, and F. Steinberg, "Potentials of prefabrication for self-help and mutual-aid housing in developing countries," *Habitat Int.*, vol. 18, no. 2, pp. 13–39, 1994.
- [7] T.-Y. Hsieh, "The economic implications of subcontracting practice on building prefabrication," *Autom. Constr.*, vol. 6, no. 3, pp. 163–174, Jun. 1997.
- [8] Faculdade de Ciências e Tecnologias da Universidade Nova de Lisboa, "Relatório do Projecto de I&D do Programa Sistema de Incentivos de Co-Promoção do QREN PAREDE ECOESTRUTURAL EL (PTQREN/21586/2011)," Faculdade de Ciências e Tecnologias da Universidade Nova de Lisboa, Caparica, Relatório de Projecto DEZ 2012, 2012.
- [9] P. Faria, V. Silva, C. Abreu, and C. Pereira, "Caracterização de betão com terra para aplicação em construção modular prefabricada," presented at the 2º CIHEL - Congresso Internacional da Habitação no Espaço Lusófono, Lisboa, 2013, p. 363.
- [10] Faculdade de Ciências e Tecnologias da Universidade Nova de Lisboa, "Relatório do Projecto de I&D do Programa Sistema de Incentivos de Co-Promoção do QREN PAREDE ECOESTRUTURAL EL (PTQREN/21586/2011)," Faculdade de Ciências e Tecnologias da Universidade Nova de Lisboa, Caparica, Relatório de Projecto DEZ 2013, 2013.
- [11] A. Brás, M. Leal, and P. Faria, "Cement-cork mortars for thermal bridges correction. Comparison with cement-EPS mortars performance," *Constr. Build. Mater.*, vol. 49, pp. 315–327, 2013.
- [12] T. Fontes, P. Faria, and V. Silva, "Caracterização de argamassas de cal hidráulica natural com metacaulino e resíduo cerâmico," presented at the Congresso da Construção 2012, Coimbra, 2012.
- [13] G. Matias, I. Torres, and P. Faria, "Argamassas de cal hidráulica natural com incorporação de resíduos cerâmicos," presented at the Simpósio Brasileiro de Tecnologia das Argamassas, Fortaleza, 2013.
- [14] C. Gonilho-Pereira, P. Faria, R. Figueiro, A. Martins, P. Vinagre, and S. Ratão, "Performance assessment of waste fibre-reinforced mortar," *Mater. Sci. Forum*, pp. 617–622, 2013.
- [15] A. Pires and P. Faria, "Comportamento higroscópico de argamassas para reboco," presented at the International Conference on Vernacular Architecture 7º ATP, Vila Nova de Cerveira, pp. 16–20.
- [16] J. Rabi, S. Santos, and H. Savastano, "Agricultural Wastes as Building Materials: Properties, Performance and Applications," *Build. Mater. Propr. Perform. Appl.*, 2010.
- [17] D. Bogati, "Cellulose Based Biochemicals," Bachelor Thesis, Saimaa University of Applied Sciences, Finland, 2011.
- [18] C. Pimentel, "Polpação artesanal do pseudocaule da bananeira (*Musa* sp)," Dissertação, Universidade Federal Rural do Rio de Janeiro - Instituto de Florestas, Rio de Janeiro, 2010.